Impact of plasmonic bowtie nanoantennas and nanocavities on the dynamics of nearby nanoemitters

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Abstract

Metallic nanoparticles exert a strong influence on the electrodynamics and mechanical dynamics of nanoemitters in their vicinity. Transformation optics can provide analytical descriptions and physical insight on these scenarios. As a case of study, we discuss the use of conformal transformation to understand the nonradiative Purcell enhancement and the optical forces experienced by nanoemitters nearby bowtie nanocavities and nanoantennas.

1. Introduction

Recent advances in nanofabrication has made it possible to fabricate nanostructures with a wide range of topologies [1]. This flexibility in attainable topologies opens endless possibilities, but at the same time makes the optimization of designs more challenging. Full-wave simulations can assist in the design process, but they have two main disadvantages compared to analytical solutions: computational burden that can potentially be unaffordable and limited physical insight.

Among the limited number of existing analytical techniques suitable for nanoplasmonics, transformation optics [2] is becoming the norm given its rigor and accuracy, which have made it possible to have analytical electromagnetic descriptions of crescent-shaped [3], cylindrical sector [4], bowtie [5] and tripod nanoantennas [6], as well as ring-disk [7] and crescent-shaped nanocavities [8]. This success should not come as a surprise though since conformal transformation was already used successfully in microwave engineering to provide analytical description of planar transmission lines [9].

Inspired by [2]-[8],[10] we investigate analytically and numerically the Purcell enhancement and the optical forces experienced by a nanoemitter (modelled as a point dipole) inside a 20 nm inner diameter bowtie nanocavity [11] and we also unveil hidden symmetries in bowtie nanocavities and 20 nm outer diamter nanoantennas.

2. Conformal mapping

Given the subwavelength diameter of the plasmonic structures under study, we assume a quasi-static problem. In this case, the electric and magnetic fields are decoupled and the former can be described by an electrostatic potential satisfying Laplace's equation.

By applying the conformal transformation $z = \ln(z'/a)$, the bowtie topologies shown on the left-hand side of Fig. 1 can be transformed into the geometries shown on the right-hand side of Fig. 1. Here $z = x + iy$ and $z' = x' + iy'$ correspond to the spatial coordinates in the transformed and original frames, respectively, and a is the distance between the nanoemitter and the coordinate origin. Notice that the nanocavity in panel (c) and the nanoantenna in panel (e) have mirror symmetric transformed spaces (see Fig. 1(d,f)).

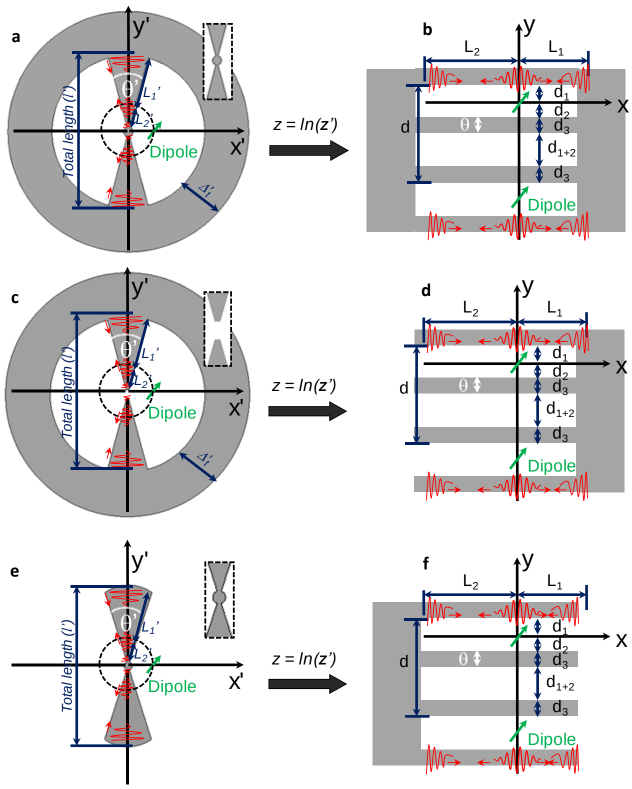

Figure 1: (a, c, e) bowtie nanocavities and nanoantenna. (b, d, f) electromagnetic equivalent transformed scenario that is analytically solvable.

The transformed space preserved the physics all the original space. Hence, the potential and power dissipation in the transformed space, $P_{\text{abs}}^{(x,y)}$, are the same as those of the original space. Given the simplicity of the transformed space,

$$P_{\text{nr}} = P_{\text{abs}}^{(x',y')} = P_{\text{abs}}^{(x,y)} = -\frac{1}{2}\omega \text{Im}\{\vec{p}^{*}\vec{E}_{1}^{s}(x,y)\} = \\ = -\tfrac{1}{2}\omega \text{Im}\{p_x^{*}E_{1x}^{s}(x,y) + p_y^{*}E_{1y}^{s}(x,y)\}, \quad (1)$$

where P_{nr} is the nonradiative power emission by the dipole source, $\vec{p}^{*}$ is the dipole moment of the nanoemitter, $\omega = 2\pi c/\lambda_0$ is the angular frequency at the operation wavelength λ_0 and c is the velocity of light in vacuum. Additionally, the nonradiative Purcell enhancement spectra is given by $P_{\text{nr}}(\omega)/P_0(\omega)$, where $P_0(\omega)$ is the power radiated by the dipole in free space. From the potential one can compute the electric field and then the optical force using the Maxwell stress tensor.

3. Results and Discussion

The nonradiative Purcell enhancement for a horizontally- and vertically-polarized dipole nearby the different geometries described in Fig. 1 is shown in Fig. 2. One can see the strong influence that the center of the nanostructure plays. Full-wave simulations (Comsol Multiphysics®) of the original space (Fig. 1(a, c, e))) agree very well with the analytical calculations (Fig. 1(b, d, f)).

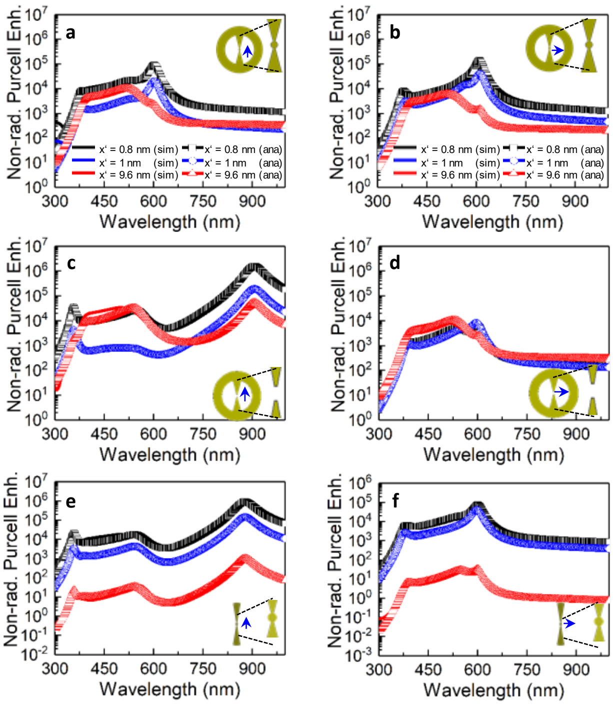

Figure 2: Numerical (solid lines) and analytical (symbols) results of the nonradiative Purcell enhancement under vertical (first column) and horizontal (second column) polarization of the dipole placed at different positions along the *x'*-axis. (a, b) bowtie nanocavity with connected metal arms; (c, d) bowtie nanocavitiy with disconnected metal arms; (e, f) bowtie nanoantenna with connected arms.

4. Conclusions

Conformal transmission is utilized to understand the physics in nanoplasmonic scenarios involving a nanoemitter and bowtie-shaped plasmonic nanostructures. The underlying mechanisms are easily unveiled by inspection of the transformed space. Also, within the transformed space a hidden symmetry between the bowtie nanocavity with disconnected metal arms and the bowtie nanoantenna with connected arms is clearly shown.

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